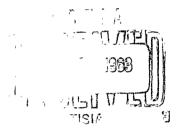FUTURE STUDY AREAS IN REINFORCED
PLASTICS FOR UNDERWATER ORDNANCE
AND DEEP SUBMERGENCE CONSTRUCTIONS

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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FUTURE STUDY AREAS IN REINFORCED PLASTICS FOR
UNDERWATER ORDNANCE AND DEEP SUBMERGENCE CONSTRUCTIONS

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ABSTRACT: In the not too distant past, glass reinforced plastics became
accepted as engineering materials for the construction of external pressure
vessels for underwater ordnance. Typical structures such as mine cases and
weapons housings are in use today, subject to moderate hydrostatic pressure
environments of relatively short durations. Meanwhile, these same materials
have come actively into consideration for use in deep submergence vessels.
This interest arises because limited tests indicate the possibility of
decided weight savings over candidate metallic materials. However, the
ordnance experiences teach that there are still performance problems with
glass laminates, due to their anisotropic and viscoelastic nature, to be
more fully understood and solved in the areas of creep, fatigue, resistance
to shock loadings, and the engineering of joints, openings and attachments
in structures. These problems, which one may expect will be aggravated by
the very high pressures to be withstood in the new application, are the
subject of this report and are broadly discussed in terms of future work
plans. Specific study programs on general external pressure vessel problems
are also suggested. It is recommended that studies such as these be under-
taken both to improve the state-of-the-art for ordnance constructions and
to prove the feasibility of using reinforced plastics materials for deep
submergence structures.

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Future Study Areas in Reinforced Plastics for Underwater Ordnance
and Deep Submergence Constructions

A great interest is currently being displayed in glass reinforced plastics
for the construction of deep submergence vessels. However, such applica-
tions call for materials and structures information beyond that available.
There is, therefore, a real need to recount the old experiences and to
determine their teachings in regard to sound approaches to today's new
problems. This report has been prepared, as a long range planning effort,
toward accomplishing the above. An attempt is made to set forth those
phases of materials research and development which are considered to be
the most important ones toward assuring definitive feasibility studies on
the use of plastics for deep submergence purposes. Obviously, these same
studies promise to give important data that will be usable in the improve-
ment of our present and future ordnance applications as well.

Many of the views expressed herein are solely those of the author, but
others represent a consensus of many opinions. Deletions, additions, and
refinements of these concepts are to be expected as work in this area of
engineering progresses. Nevertheless, it is hoped that this report will
be helpful to all who are engaged in external pressure vessel development.

                                    R. E. ODENING
                                    Captain, USN
                                    Commander

                                    ALBERT LIGHTBODY
                                    By direction

CONTENTS

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INTRODUCTION

1. Oceanographers have determined that over 70% of the world's ocean bottoms lie at depths of from 10,000 to 20,000 feet (ref. (a)). With the exception of the very special and limited means now at man's disposal for probing these reaches, we are denied the opportunity to explore most of this tremendous water space. New vessels are, therefore, needed to extend our ocean studies and this in turn creates a requirement for deep submergence hulls of novel designs and of lightweight materials of construction.

2. It is not unnatural then to consider the glass reinforced plastics for this purpose, as they are rapidly increasing in importance as engineering materials for a wide variety of ordnance items. This situation has developed because these materials have specific properties, as well as combinations of properties, that are unique. They are generally nonmagnetic and nonconductive in nature. Densities are only one fourth that of steel and yet they have very useful structural characteristics. They are easily fabricated and do not require materials for their formulation which are in normal critical supply. In addition, there is an ever increasing fund of engineering experience developing on their use in specific ordnance applications.

3. One of the recent and more exciting and severe uses of the glass reinforced plastics has been in the external pressure vessel field. Mine cases and weapons housings are now giving satisfactory performance under moderately severe conditions. This has been accomplished through empirical engineering approaches and the various problems which developed have been reasonably well solved insofar as the present applications are concerned.

4. Although there is this precedence to spur us on with our desires to build deep submergence vessels of reinforced plastics, we must be prepared to cope with service requirements much beyond those with which we are already familiar. The result is that there are many questions requiring more rigorous answers than ever before. A better understanding of and data on time-to-failure characteristics, fatigue resistance, shock resistance, moisture effects on mechanical properties, etc. are needed. Also, work should be done on improved fabrication processes and the development and selection of new materials or combinations of materials to resist compression and flexural loadings.

5. In this report the state-of-the-art in the use of glass reinforced plastics for external pressure vessel construction is discussed, and the current materials and structures studies are listed. Further, those areas needing additional study for general ordnance, as well as for deep submergence applications, are broadly discussed to provide guidance for future research and development work. Certain specific study programs are appended.

BACKGROUND

I. UNIFORM EXTERNAL PRESSURE LOADING EFFECTS

6. Before one continues much further in his thinking about reinforced plastics structures for underwater usage, it is well to look more thoroughly at what is involved in this type of service. First, let us examine what happens to the gross structure, then we can consider the material itself under the prevailing stress conditions.

7. When a vessel is submerged, it becomes subject to hydrostatic pressure, which creates combined axial and radial loadings and causes compressive and flexural stresses to develop within the material of construction. As these stresses increase in severity, two modes of failure become possible. First, if the vessel is thin-walled relative to its diameter, long and not too rigidly reinforced by rings or bulkheads, it can fail by a buckling or instability mechanism. In this case, the vessel first loses its shape (reinforced plastics vessels undergo a two-lobed deformation). Then even greater stresses are introduced, exceeding the strength of the material at the points of maximum deflection, and a localized yield failure takes place. Second, if the vessel is thick-walled, otherwise rigidly supported and of short length, the stresses will build up to the point where they exceed the strength of the material and yield failure results. Thus, in the first case, rigidity of the vessel is most important, while, in the second case, high material strength characteristics are required.

8. The way in which ends are attached to a vessel will also influence its collapsing pressure resistance. Ends may simply support the tube and allow it to move on its axis and rotate, so distributing stresses, or they may restrict either or both of these movements. In addition, imperfections in the tube construction can have considerable influence on its strength characteristics. These may allow the tube to locally deform more readily, thus increasing the severity of the out-of-roundness problem and so lead to premature failure.

9. When vessels are stressed, as above, very complex demands are made on the materials of construction. Thus, one might rightfully question how well reinforced plastics, which are highly anisotropic, could be expected to perform under external pressure loading.

10. These materials derive their characteristics from the fact that the resin matrix and the reinforcement operate together by the principle of combined action to resist a given stress condition. Laminating resins are fairly weak, of low modulus, and exhibit compressive strengths varying from 15,000 to 30,000 psi. In addition, they are viscoelastic in nature and so are stress-time dependent. In contrast, the glass filaments, of which fabric and roving reinforcements are constituted, are very strong in tension but have no column loading support capability in themselves because of their extremely fine diameters and resulting short stable lengths.

However, together these two materials give fabric laminates with edgewise compressive strengths of from 50,000 to 100,000 psi, while unidirectional glass laminate values range from 100,000 to 300,000 psi. The laminate, being in effect a sandwich structure made up of alternate plies of resin and glass, exhibits the above maximum properties only in the principal directions of the glass and in the plane of the glass. Between these principal directions, and depending upon the reinforcement form, these strengths vary down to some minimum value. In the resin layer, resin properties predominate. The result is that laminate strength values vary widely, and one must know the actual direction of loading, as related to the direction of the reinforcement, before he can estimate what loads can be resisted.

11. From the above, it can be seen that glass reinforcements impart high compressive strengths only to the degree that the fibers are held in the proper position to assume the load. The resin serves to hold the glass in this position and to distribute the stresses amongst all the fibers. Thus, it is submitted to simultaneous and varying intensities of compressive, shear and tensile forces. As long as these forces are not too great and the resin is able to retain its shape and size without fracture, the load will be borne. However, with stresses applied over an extended time, the viscoelastic nature of the resin will predominate, flow will take place, and, for all practical purposes, the laminated structure will lose a significant portion of its compressive load supporting characteristic.

12. The form of the glass - whether fabric or unidirectional - apparently has considerable influence on long-term compressive stress resistance (cf. (b)). With the fabric, all the glass is mechanically tied together and must, in the main, act as a single sheet of finite thickness. Creep effects in the structure thus become limited principally to the resin interlaminar plane. Under these conditions, the greatest strains would be expected to arise in the plane parallel to that of the reinforcement and only in that direction short of rupture of the resin layer in its thin direction. With unidirectional glass, another situation holds. In its various discrete bundles or tapes, all the glass is laid down in the same principal directions. Other than through twisting and winding process induced disarrangements, each fiber is an unsupported individual except as bonded to its neighbors by the resin matrix. Now the principal direction of restraint to resin creep is along these fiber axes. In all other directions perpendicular to the fiber, resin properties control (or resin-to-glass bond strengths, should they be weaker) just as they do in the interlaminar resin layers created by the reinforcement laydown pattern used in the construction of the part. With this situation holding true, one wonders if the unidirectional laminate, although stronger in a short-term test, would not be effectively more time sensitive in regard to its compression properties than would be the fabric laminate.

13. When a section of a glass reinforced external pressure vessel under load is examined, it is seen that a complex stress situation exists. The element is under compression in circumferential, axial, and radial directions and is restrained on the inside surface only by the curved

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geometry of the vessel wall and by the mechanical integrity of the material itself. The loadings in the circumferential direction will be approximately twice those in the axial direction and both will decrease with increasing wall thickness. In contrast, the force along the inward radial direction developes only a very low compressive loading, equal to the hydrostatic pressure and independent of wall thickness. Therefore, due to the singularly high circumferential loading, the element will be most severely compressed hoopwise and will tend to deform by expansion in the other directions. These movements first will be restricted by the hydrostatic axial and radial forces present. Then, along the axial direction, once the axial hydrostatic force is neutralized, the reinforcement will develop a tension loading and another set of restraints to deformation will be established. Thus, the laminate is placed in bulk compression but with unequal forces being applied along the three loading axes. Furthermore, this bulk compression stress will be at a minimum in the outer layers of the wall, but as one moves along the radius towards the axis of the vessel, it increases in intensity to a maximum at the inner wall surface. With the maximum stress on the inside and with a minimum of restraint inward along the radius, several modes of failure become possible. Under short-term loading, the inside resin layer can fracture due to either shear or tensile loadings. If the glass-to-resin bond is poor, failure can initiate at this interface. In either case, delamination occurs and progressive catastrophic failure sets in. Under long-term loadings, or if the resin matrix has an especially low modulus, resin creep may occur with resulting buckling of the inner reinforcement layers and subsequent failure.

14. In addition to this compression loading picture, we must also account for bending forces. When the loading on a vessel is near the instability level, or if the material is creeping, out-of-roundness occurs and flexural stresses are indiced. These complex the internal stress relationships in the vessel wall by increasing the compression loading on the inside surfaces at the points where the radius is decreased most sharply and by introducing tensile stresses in the outside fibers opposite these same points. Thus, failure is quickly induced by exceeding the load bearing capacity of the material.

15. As if the above were not sufficiently complex, we must now superimpose the anisotropic characteristic of the reinforced plastic. With this it becomes next to impossible to determine what strains are set up or what their magnitudes or directions may be at any specific point within the laminate. We can postulate, however, that they will vary widely and that this variation may be quite random. Not only does the direction of the glass enhance this, but resin properties vary with their degree of polymerization within the mass, and the laminate may include flaws such as delaminations, poor resin distribution, gas bubbles, etc. which are a product of the fabrication technique. One investigator, based upon his studies of cast samples, ascribes a likely 50% loss in strength in the resin due to these flaws (ref. (c)). However, this does not mean that a similar loss of properties would be noted in a laminate.

16. From the above, it is obvious that laminate materials performance under external pressure loadings is a complex subject with many unknowns. It might even seem undesirable to consider them for this type of service. However, as evidenced by the developments discussed in the next section, reinforced plastics do quite well - in fact, better than would be intuitively expected and better than would be predicted from classical data. The problem becomes that of recognizing the important factors involved, of putting them in proper perspective one to another, and of developing the necessary data and experience for their judicial application to underwater structural service.

II. REINFORCED PLASTICS EXTERNAL PRESSURE VESSEL DEVELOPMENTS

17. Our present ability to apply glass reinforced plastics as primary underwater structures to resist external pressures grew empirically through the pursuit of several ordnance projects. The first interest originated with development of the Weapon "A" housing in the period 1947 through 1949 (ref. (d)). Both the U. S. Naval Ordnance Laboratory, White Oak and the U. S. Naval Ordnance Test Station, China Lake were engaged in this project, and a plastics body was developed following a generally empirical approach. Glass mat reinforcement bonded with a polyester resin was first used. Later, the mat was replaced by a glass fabric, which, with the polyester resin, became the final material of construction. By the use of these materials, a strong, lightweight, nonmagnetic and nonconductive vessel was provided. It was designed to fully support the hydrostatic pressures involved, but in actual use was supported internally by an explosive loading.

18. As part of this development, studies were made at NOL on the strengths of various plastics materials combinations. Techniques were also developed for measuring the collapsing pressures of vessels and for determining their deformations during pressurization (refs. (e) and (f)). The literature was searched, appropriate collapsing pressure formulas for metal structures were selected, and tests were made on simple plastics tubes to determine materials constants so that these formulas could be used for estimating the strengths of plastics structures. The initial work was done at this time in relating collapsing pressure failure predictions by means of the Windenberg-Trilling formula (ref. (g)) to laboratory test data collected on cylinders laminated of glass fabrics and polyester resins.

19. Following the Weapon "A" work and up until 1955, NOL was interested in using reinforced plastics in the construction of mine cases and different torpedo hull sections. Several such structures were empirically developed and evaluated with varying degrees of success both as research items and as ordnance hardware. Again, glass fabric reinforcements bonded with polyester resins were favored; however, both the phenolic and epoxy resins were also considered and the phenolics were successfully used in one torpedo part. About this same time, a private company developed a glass mat polyester centrifugally cast part, which served as a hull section for a small torpedo and was found to be acceptable in performance.

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20. In 1951, development work was started on the Mine Mk 57, and a reinforced plastics case was specified. Because of the lack of general data on reinforced plastics in resisting external pressures, a half-scale mine model program was also undertaken to supply the missing information. A simple ribbed vessel with right circular cylindrical sidewalls and a hemispherical end was selected for test. During the program many variables were examined: effect of materials and construction, ribbing reinforcement, dimensional parameters, short-term pressure resistance, long-term pressure resistance, resistance to shock loading, etc. With this body of information, it became possible to make initial prototype designs for limited types of underwater housings made of specific materials combinations (refs. (h) and (b)). The laboratory work on the half-scale program was concluded in June 1958. Meanwhile, a mine case of glass fabric bonded with an epoxy resin and weighing about 400 pounds was developed. This case is now ready for its final stages of fleet acceptance testing.

21. Glass roving materials became of interest near the end of the half-scale program and were considered as a replacement for the glass fabric. However, the test data accumulated could not support a change. The epoxy bonded structures, then available, failed to demonstrate sufficient resistance to long-term hydrostatic pressure loading conditions.

22. Beginning in 1957, the Bureau of Ships, the Office of Naval Research, and the David Taylor Model Basin instituted studies on glass reinforced plastics for the construction of deep submergence submarine hulls (refs. (a), (i) and (j)). The requirements here, though similar in nature to those of the ordnance applications, presented problems much more severe than previously encountered. Obviously, thick-walled sections were required in contrast to thin-walled ones. Also, the overall sizes had to be much larger. Limited tests were run on ribbed and unribbed tubular model configurations of fairly thick-walled design. The materials used were epoxy resin bonded unidirectional glass in the form of sheets and tapes. These evaluations indicated that plastics might indeed be superior to metals for deep submergence use.

23. Later, DTMB evaluated Pyrex glass cylinders as a possible material of construction (ref. (k)). These vessels developed collapsing pressure resistances as high as 15,000 psi and circumferential wall compressive stresses of 97,000 psi. Such data as this, when considered in terms of strength-weight ratios, also make glass look very promising, in the initial phases, for external pressure resistant structures.

24. Sometime in 1959, NOTS became interested in plastics underwater structures (ref. (1)). They set up a program and evaluated simple tubes for collapsing pressure resistance and static diametrical loadings. Since their first report, there has been no further word on this work other than that selected syntatic plastics foams offer some promise as filler materials around pressure hull structures at moderate pressure levels.

25. The above, then, is a brief summary of the efforts put forth on reinforced plastics external pressure vessels. Development goals were accomplished for the moderate hydrostatic pressures and other service requirements specified for the individual ordnance uses. However, still better engineering solutions could be had for many aspects of these designs.

III. EXTERNAL PRESSURE VESSEL STRENGTH CALCULATIONS

26. Several formulas exist which can be used to predict the collapsing pressure resistance of a vessel. These were first developed for boiler tube calculations where only radial forces are involved. Then they were modified to fit more general cases, including vessels with ribs, closed ends, and combined axial-radial loadings. At present, a very practical formula is that developed by Windenberg and Trilling (ref. (g)), based upon Von Mises' earlier and more sophisticated theoretical derivations. With a range of experimental data on structural shapes, it is possible to use this formula with a fair degree of accuracy to predict the performance of reinforced plastics vessels, even though it was developed for thin shells of isotropic materials. In the laboratory, its use has been carried from the instability failure region into the yield failure region in an empirical manner by varying the materials property data introduced in the specific calculation (refs. (h) and (b)). Although this work has all been with relatively thin-walled vessels which have been reinforced by ribs, more recent work has been done with thick-walled vessels (refs. (a), (l) and (j)). Again, the general Windenberg-Trilling formula has been shown to be useful and to yield calculated values which are generally within 5% of experimental values.

27. In addition to the above, formulas exist for calculating ribbing for stiffening cylindrical shapes (ref. (m)). Most generally, a rib which fails at the same instant the sidewall does is preferred. Also, satisfactory calculations can be made for hemispherical shapes, provided model data again are available (ref. (d)). Thus, it is not too difficult to predict thin-walled vessel performance (and thick-walled to a lesser extent) for short-term loading conditions of a duration which permits no changes to take place in material properties and which excludes creep and fatigue effects from developing.

28. To date, no one has applied any methods of predicting compressive and flexural strength retention which take into account the typical military situation in which time and other environmental variables become so very important. Such characteristics as material loss of strength due to water exposure, fatigue resistance due to repeated diving and surfacing maneuvers, time-to-failure properties for sustained pressure loadings, general creep and viscoelastic behavior of reinforced plastics structures, and resistance to shock loadings can only be estimated intuitively based upon a very meager amount of model and prototype experience. However, Goldfine (ref. (n)) has suggested a method of calculation for predicting time-to-failure

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under constant load, which deserves further consideration in the deep sub-
mergence application.

IV. CURRENT ENGINEERING STUDIES

29. Some testing is still continuing on Mk 57 mine cases; of particular
interest being time-to-failure measurements. Two production type cases have
been under continuous hydrostatic pressure for 172 and 239 days (23 November
1962) at a circumferential compressive stress loading of 7,300 psi. These
cases indicate no signs of failures as is to be expected, since the half-
scale model work demonstrated that one material-design combination could
withstand a 19,700 psi stress for a year's time (ref. (b)) without failure.
Other than the above, and a contractural effort to make a prototype filament
wound Mk 57 mine case, there appears to be no significant work in progress
at present toward improving either plastic materials or designs for general
underwater ordnance use.

30. However, the interest in deep submergence applications is still
very much alive and all efforts are pointed in this direction. Materials
and structures investigations are active, and contracts, sponsored by
BuShips and BuWeps, are in force to provide additional engineering data
toward increasing the present state-of-the-art. A list of these contracts
and their goals is presented in Appendix I. Such factors as thickness
effects on laminate properties, material properties influencing creep and
fatigue, high strength-high modulus materials development, use of large
diameter glass fibers, improved resins, hollow glass fibers, and compression
testing techniques are under investigation. The hope is to demonstrate that
a practical material can be made available which will have an edge com-
pression strength of at least 150,000 psi, will resist cyclic fatigue up
to 50,000 cycles, and which will resist creep and buckling with little
deleterious effects due to water absorption at pressures up to 10,000 psi.
At the same time, a much improved understanding of materials' response
characteristics under biaxial compression loading is being sought. It is
then proposed that large scale models be constructed and the feasibility of
using reinforced plastics for deep submergence hulls be critically deter-
mined through structure performance testing.

V. PRESENT STATE-OF-THE-ART

31. Based upon laboratory development experiences and studies on rein-
forced plastics external pressure vessels, limited vessel performance
estimates can now be made. Most of the experimental work has been on
glass fabric reinforced units bonded with selected polyester and epoxy type
formulations. Data have been collected on the effect of various geometri-
cal parameters on the properties of these units and, to a limited degree,
on their service performance. These data are useful with the Windenberg-
Trilling formula for performing initial prototype design calculations.

32. In addition to the above, limited tests have been made on glass
roving and unidirectional glass reinforced vessels. In contrast to the

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experience with the glass fabric vessels, experience with these for ordnance has been disappointing, although some of the more recent data collected on deep submergence studies are such as to make the unidirectional glass reinforced vessels look very promising. These recent data have been on thick-walled constructions and the Windenberg-Trilling formula again has been found applicable for limited strength predictions.

33. The present state-of-the-art permits only prototype and test model designs to be made, based upon limited materials selections and with only slight service performance data behind it. Not enough is known to properly minimize weight configurations. The long-time pressure resistance and the underwater shock resistance pictures have been only vaguely hinted at. Many additional materials selections might be suitable and a broad study of fabrication techniques is lacking. Fatigue data are lacking and a much better understanding of the viscoelastic nature of external pressure vessels is needed.

AREAS FOR CONTINUED AND FUTURE WORK

34. It is obvious from the current state-of-the-art that much work is required in the future if reinforced plastics are to be advanced in their application to underwater use - for general ordnance and, in particular, for deep submergence. Only through such work can proper materials selections be made and adequate designs assured. To reach these goals, two broad areas of effort are required, one in research and the other in development, as pictured in Table I. The development part may be considered as covering that work which must be accomplished in order to build an experimental deep submergence vessel for feasibility evaluation in the shortest possible time. Progress here will probably be limited to the use of present materials and methods of fabrication with, at the most, only minor modifications and improvements. Through research, on the other hand, new materials and methods can be sought which will enable more efficient vessels to be developed in the future.

35. Below is a limited discussion of the several aspects of the development and research work pertinent to deep submergence. Briefly, an attempt is made to point out the directions that should be taken in prosecuting this work. In those areas of greatest interest to NOL, specific programs have been included in the appendices. The ideas presented are based to a large degree upon development experiences on ordnance for moderate hydrostatic pressure resistance.

I. NEEDED DEVELOPMENT WORK

A. Properties of Materials

36. Not too much information is available on the strength permanence of laminate materials under long-term storage and underwater immersion conditions. What is known is that glass finish-resin-curing agent

combinations can be selected which will give increased permanence when exposed to adverse temperature-humidity conditions (ref. (o)). With the continued development of resins and curing agents, it is reasonable to assume that even more optimum combinations can be selected now than at the time of reference (o). These selections could be accomplished through a survey of existing materials and an evaluation of their strength retention characteristics after typical environmental cycles. Such an effort should be considered as part of Contracts NObs-84672 and NObs-86307 of Appendix I.

37. Coupled with the above, these materials examinations should also be analyzed for ease of fabrication and for reproducibility of properties and high level of properties obtainable in a fabricated form. Then selections could be made as to the strongest materials for prototype construction.

B. Properties of Structures

38. Additional data are needed on the strengths of glass reinforced laminate structures. In particular, structures reinforced with glass rovings or tapes should be evaluated for short-term collapsing pressure resistance. Data are required on thin-walled vessels for ordnance, as well as on thick-walled constructions for the first deep submergence vessel prototypes. Elements of this need are covered in Appendix II.

39. Along with short-term strengths, long-term load bearing capabilities, as well as structural fatigue resistance, should be improved. One approach to this is to control the viscoelastic nature of the resin matrix of the laminate build-up, which is emphasized when the material is under compression or flexural loading. By mechanical means, an interlocking of glass reinforcement layers might be provided and in effect provide three-dimensional reinforcement for the vessel, thus decreasing the strength controlling role of the resin. There are several practical approaches toward this concept, as outlined in Appendix II, which it is expected will be under investigation shortly.

40. In the course of the above, it is desirable that much additional data be collected on the long-term pressure resistance of vessels for empirical design purposes. These should be sufficient so that design allowances can be established and so preclude the estimation of this characteristic from other unrelated data and experiences. Likewise, there is no data to speak of on the fatigue resistance of external pressure vessels and test methods must be devised and data accumulated on this property. Contract NObs-86461, Appendix I, should eventually include this latter point, while Appendix IV also suggests another approach toward developing a body of information.

41. The problem of underwater shock loading has been only sketchily explored. Much more effort is needed on the evaluation of materials and structures from this viewpoint. The low modulus characteristics of the

reinforced plastics make such an investigation especially important because of the large and possibly damaging deformations that may occur, particularly around joints and openings and at machinery attachments. Appendix III presents a program to elucidate the shock resistance characteristics of plastics vessels.

42. With any practical vessel there must be joints, openings, and attachments, or the equivalent of these. They are relatively easy to provide in metal structures but in reinforced plastics severe engineering problems are encountered, because the material cannot be welded or otherwise fuzed together. Present techniques involve adhesive joints, fabrication of one section over a previously fabricated part, incorporation of metal joint rings, and bolts passing through the body of the structure, for example. Much improvement in these techniques is demanded. Efforts should be made to eliminate as many adhesive joints as possible. Joint designs should strive to allow the mating sections to deform in the same mode and to the same degree when the structure is strained. This is of the greatest importance for reliability and long life of the vessel, especially in terms of its fatigue and shock loading resistance. Without this ability, low level strengths and a tendency for weepage to occur will characterize the joint and attachment areas. A few possible joint designs are suggested in reference (b).

43. Present techniques for manufacturing reinforced plastics are, in the main, geared to the production of rather thin-walled objects of fairly limited size. However, as of August 1962, one manufacturer has demonstrated that a one-piece rocket motor case, 13 feet in diameter by 25 feet in length and encorporating approximately 12,500 pounds of glass and resin, is feasible (ref. (p)). It required only ten days to make by glass roving winding techniques. Although the vessel is termed "thick-walled," its sidewall is estimated to be only a little over one inch in thickness (ten-inch or greater thickness requirements are anticipated for deep submergence vessels). At this time nothing is known about the quality of this vessel.

44. One unique thing about the above construction is that it has been made by the manufacturer's own somewhat esoteric process. Another manufacturer making the same piece would undoubtedly go about the job in a different manner. Although the two units would look alike when completed, no assurances could be given as to the degree to which they would perform alike unless there could be an exchange of materials and process information beforehand. Because of this, there is a crying need for a better understanding of the important materials and laminating process factors and for their careful and complete specification. For deep submergence hull constructions, every step of the materials selection and acceptance and of the laminating process should be under the tightest of controls. To do this, more information is needed on the process. Although some is already being collected on rocket motor case constructions, it will deal with thin-walled fabrications, whereas data are required on truly thick-walled constructions. With these it might be logically expected that the

process controls will be far more critical. Contract NObs-86406, Appendix I, will provide some information in this area as will the program outlined in Appendix II.

C. Design Criteria

45. Many of today's designs in reinforced plastics for deep submergence are based upon right circular cylindrical sidewalls reinforced by circumferential ribs and capped at the ends by nearly hemispherical domes. New concepts in design should be explored. Longitudinal stringers in conjunction with circumferential ribbing could lead to more efficient constructions. Foam plastics might be incorporated in some of the more moderate pressure applications. It is understood that some promise in this direction using syntactic foams has been demonstrated by NOTS. A combination of double truncated spherical sections joined together has been suggested in the past by Pugh of NOL for mine cases and has also been considered for metal structures (ref. (b)). These could be easily surfaced on the outside with a straight cylinder and the void between the two filled with foamed plastic. Would this approach or some variation of it give us the most efficient structural configuration?

46. Composite structures should also be carefully considered. In simple form, a titanium or aluminum thin-walled shell - or even a shell of glass or ceramic - could be used to form the inner layer of the pressure hull and then this could be covered on the outside with reinforced plastics. A slightly more complex structure would involve, for example, titanium inside covered by aluminum and then sheathed in filament wound plastics with the glass mainly in the hoop direction. Thus, a gradation of mechanical properties could be built up. The metal sections would be kept thin enough so that their fabrication would be easy and economical. In addition, a situation would be provided wherein the plastic would now be supported against creep deformation in all directions and so one would expect it to be a more efficient material. The metal inner surface would also decrease the many problems of openings, joints, and attachments. In addition, if sufficiently close enough shock impedance matches between the materials layers could be established, then a more shock resistant construction could possibly evolve. Finally, the structure could be also covered on the outside with a metal layer to provide protection against mechanical damage and moisture penetration.

D. Fabrication Technology

47. Ease of fabrication and low cost are certainly to be sought. However, at the present time these will probably be controlled more by the materials selected and the design concepts used rather than by any other factors. At the present state-of-the-art, it would be well to dwell more on feasibility studies of reinforced plastics for deep submergence rather than how much they might cost, since their cost will tend to be high in the initial stages, just as with the competing metallics.

48. Definite engineering problems are created by the need for techniques of repair and maintenance. For reinforced plastics deep submergence vessels, where the strength and permanence characteristics are so critical, it is suggested that these needs be minimized by providing other solutions to the problem. The most conservative approach would be to consider repairs only as emergency or short-term expediencies. Thus, the low-strength repaired areas would not have to be taken into account in terms of vessel performance for any extended time period. Efforts should be made to develop overall vessel designs so that damaged sections could be replaced and thus eliminate the need for extensive repairs and maintenance.

II. NEEDED RESEARCH WORK

A. Properties of Materials

49. As discussed earlier, external pressures result in compressive and flexural loadings in a vessel sidewall, which, with reinforced plastics, causes the resin matrix to play a dominant role in determining the composite strength. These resins are low strength, highly viscoelastic materials, and, in compressive loading, the ability of glass to reinforce this viscoelastic mass is related in a complex manner to the ability of the resin to hold the glass in position and prevent column buckling. Even so, unreinforced resins do a remarkably good job of resisting short-term collapsing pressures, as is evidenced by unpublished NOL data. However, improved laminating polymers are still needed to give increased long-term load resistance. They should be decidedly more elastic in nature, stronger and stiffer in compression and shear but still have the desirable handling properties of the present materials, as well as retaining their low density, nonconductive and nonmagnetic characteristics. It would also be ideal from the fabrication viewpoint if they could have zero shrinkage characteristics on polymerization. In addition, these resins should be formulated for permanence, temperature-humidity cycling resistance, and water resistance. It would be desirable if the resin could be caused to polymerize to a mass with highly three-dimensional crosslinking and to develop the creep and shear resistance of glass itself. Then, one might obtain the equivalent of a glass laminated glass structure, or, conceivably, the resin alone could serve as the structural material for many applications.

50. Glass fiber configuration and formulation changes offer possibilities of increasing laminate strengths and efficiencies. Some work is already in progress on hollow filaments to increase efficiency; however, more studies are needed along these lines, as well as looking at other possible filament forms. Considerations of large diameter filaments should be extended. It is possible that diameter should vary with size of vessel to provide optimum properties. If such were found to be feasible, then it might be desirable to draw these large filaments or rods off the top of molten batches of glass and so enjoy the maximum strength of glass, even in this massive form (as shown to be possible by Dr. W. F. Thomas of Cardiff, Wales, ref. (q)). At the same time it might be well to consider a change in shape of the "fiber" for better packing; however, column buckling principles should always be kept in mind.

51. Glass formulations, with only a few exceptions, have tended to remain the same for almost the lifetime of the reinforced plastics industry. Also, the reasons why the present popular formulations have been selected are not necessarily of prime importance to underwater usage. A completely new approach should be made in this area. New glass formulations should be considered - maybe something other than "glass" would be desirable. Various whisker materials are being studied today. These could be combined as staple fiber yarns with continuous glass filament yarns to give a roving material of improved characteristics for three-dimensional reinforcement. Present considerations of high modulus filament formulations should continue. In other areas, to what extent should metal fibers (Be, B, etc.) be considered? Could metal coated organic or glass filaments be of value?

52. Chemical finishes for glass have been shown to be very desirable in increasing the wet-strength retention and permanence of laminates. The role of these finishes is a very complex one and is yet to be understood. With new changes in resin and glass formulations, it can be expected that this area of study will become even more important than it is now. Efforts to understand finish action and to provide improved ones should continue.

53. In the future, some thought should be given toward providing increased chemical compatibility between reinforcement, finish, and resin. Thus, the glass might be formulated to aid chemical bonding to the finish just as we now try to make the finish and resin mutually reactive. New test methods are also needed for the study of the glass-finish-resin reaction zone. These should be so developed that they will adequately demonstrate the effects created by known causes and so be of a more enlightening nature.

54. Only minimal data exist on the creep and fatigue resistances of glass roving reinforced materials and structures for external pressure resistance. Materials studies should be instituted in this area, both on standard specimens and model structures. NOL ring specimens would be ideal for this purpose and can be tested for both creep and fatigue in the new NOL ring compression tester. Appendix IV presents a program based upon this approach which could provide much information on materials and process variations. Such a program should be supplemented by one on model structures so as to study multi-axial loading effects.

55. Shock resistance of plastics is a little understood subject. At best, only comparative data exist which neither helps one to understand how shock effects materials nor provides design information. Rather basic studies are needed, first on "ideal" plastics and then on composite materials, to explore the general phenomena. At this time it would be rather difficult to outline all the benefits to be gained from such an effort, but it is to be expected that a better understanding of shock effects will eventually lead to more efficient design of shock resistant structures. Appendix IV, in part, discusses an initial approach to such a study.

56. Permanence of mechanical properties is vital for any laminate structure which must be operable in water for long periods - in some cases from 5 to 20 years. Since some glass laminates have been deficient in this respect in the past, fears naturally arise in the minds of many when their use is proposed for deep submergence. Dire predictions are immediately made based upon some of the conventional laboratory data available. However, it should be noted that the experiences and data accumulated so far on vessels under wet compressive loading (refs. (d) and (b)) do not support these fears. Because of this overall situation, there is a need for more specific data on the mechanism of moisture penetration into a laminate and on means for its control. It is also desirable to learn more exactly how the properties of the material can become altered due to water pick-up and what equilibrium strength profile will develop in the wall of a structure when there is water under pressure on one side only. A brief program in this area of study is suggested in Appendix V. Work has also commenced on Contract NObs-86871, Appendix I, but it is not yet clear what will be accomplished.

57. Some experiences have been had with laminates immersed in water where after a period of time there has been a loss of surface resin. This has been noted only in shallow waters, but now there is a need to develop information for deep water submergence. Any unusual or reversed effects, as noted with the metallics, should be sought and a measure of the degree to which water "corrodes" plastics at different depths should be determined.

58. There is a strong feeling abroad that we really have no good ways by which to determine laminate properties. Our techniques are mainly destructive and almost invariably patterned after standard tests developed for the more isotropic metallics. Realizing the short-comings of this sort of testing, we then place our final reliance in some sort of prototype test under simulated or actual service conditions. The overall result is that with the highly variable and anisotropic glass reinforced plastics, these methods do not give us any well defined insight into material properties.

59. It is suggested that the above status quo should be attacked. New methods should be sought and brought in from other fields, as well as being developed. One approach is to borrow from the polymer researchers. Could their methods of dynamic testing over wide temperature ranges utilizing a high frequency driving force be adopted? Resin matrix materials could be tested with and without typical reinforcements. Controls over the resin polymerization could be exercised through electrical volume resistivity measurements so that variations in polymerization variables and resin properties could be studied and separated from reinforcement effects. By such an approach not only might data on the viscoelastic nature of laminates be gained, but this might also lead to a better understanding of failure mechanisms.

60. Techniques other than the above might involve encorporating the specimen into a pendulum support arm and recording the ability of different

materials to dampen the oscillatory action of the system. Both of these techniques have been found to be very useful with linear polymers, but only the barest of exploratory work has been done on crosslinked materials. Plans are in progress at the Laboratory toward proposing work in this area.

B. Properties of Structures

61. Attempts to understand the failure mechanism in laminate materials should be carried over into structural shapes. Methods exist for determining instability, collapsing pressure strengths, and deformation of vessels by nondestructive means, but these give but few clues as to stress distributions in the sidewalls. If the vessel is taken to actual failure, then so much energy is released that no conclusions can be reached based upon examination of the remains. Techniques are needed to follow stress build-up in the ordinary short-time pressure tests. In long-term tests and under cyclic fatigue conditions, there should be means to follow stress build-up and the redistribution of stress with time and cycling. Ideally, these techniques should not only give the resulting web stress patterns, but there should be means of looking at the stress distributions throughout the sidewall thickness both near inserts and openings and through the unmodified sections. Such are needed to make one's failure analysis of these composite materials more useful.

62. Although it is generally realized, it should be reemphasized that nondestructive test methods are desperately needed for the quality control and acceptance testing of structures. There are many efforts afoot designed to provide adequate inspection techniques, but it still appears that new concepts are demanded. Our present plight is probably the results of a not-too-serious need in the past, as well as too scattered and too little effort in this direction. A serious, well supported, well conceived nondestructive test development program should be commenced at once.

C. Design Criteria

63. As new materials and new processes for reinforced plastics become available, new design concepts should be developed. A continuous search for new possibilities should be maintained and might best be part of the regular design effort in deep submergence vessels.

SUMMARY

64. Limited laboratory data and practical engineering experience exist on the use of reinforced plastics for the construction of external pressure vessels. This information is largely confined to that gathered on the development of structures for use at moderate hydrostatic pressures. Although these applications have been generally successful, there are still many problem areas needing more refined engineering solutions. For example: better time-to-failure characteristics are desirable, improved shock

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resistance is desirable, improved designs for hull openings are needed, and better materials and processes are needed.

65. Now, when deep submergence structural applications at very high hydrostatic pressure levels are considered, the problems raised by present usage become critical. Much work is, therefore, needed to develop an increased background of engineering data, improved materials and processes, and improved designs. Only then can the feasibility of a glass reinforced plastics deep submergence vessel be accurately determined.

RECOMMENDATIONS

66. At the present state-of-the-art, any efforts to quickly produce a working model of a deep submergence vessel should be prosecuted based upon present materials and methods. It is possible that a design based upon spherical sections and constructed of a metal-reinforced plastic composite would be the most feasible approach. Only a minimum of assistance from subsequent materials research and development programs should be expected in this effort.

67. Meanwhile, process and materials development efforts should be commenced. Attempts should be made to control the viscoelastic nature of the resin matrix of the laminate. Data should be collected on creep, time-to-failure, and fatigue resistance of laminate materials and structures. Underwater permanence and shock resistance should be studied. Better design criteria and analysis of failure techniques should be established. Suggested programs in this area are included in Appendix II through V. These data, once collected, should also be applied to the less spectacular but nevertheless very important ordnance applications toward improving current performance efficiencies and reliability.

68. The area of basic materials research should not be overlooked due to the press of the development work, and everything possible should be done to understand the performance of laminated plastics in the deep submergence environment. New and unique reinforcements, resin matrices, and other materials concepts should be energetically sought.

69. In the interim, our ideas on the use of glass reinforced plastics should not be judged alone by the most severe requirements conceivable. We must recognize that all materials have limitations and that they must be used only with due respect for these limitations. The fact that a material will not suffice for the most rugged application does not mean, that with all things considered, it cannot be the best available for some other use. We need deep submergence combat submarines, it is true. But what are our needs for various deep submergence research vessels with which to explore our ocean depths? Many types of vessels will undoubtedly be required if man is to gain control and use of this vast "inner space," as proposed by Gentry (ref. (r)) and many many others since the time of Jules Verne.

TABLE I

THE DEEP SUBMERGENCE VESSEL PROBLEM*

Problem Elements	Development Area	Research Area
Properties of Materials	Mechanical Strength Permanence**	Resin Formulations**
	New Materials Selections	Glass Formulations
		Glass Finishes
		Creep and Fatigue Resistance**
		Shock Resistance**
		Moisture Transmission Phenomenon
		Water Corrosion
		Better Ways to Express Mechanical Properties of Laminates**
Properties of Structures	Strength Characteristics	Failure Analysis for Short and Long-Term
	Creep and Fatigue Resistance**	Loading and for Dynamics Loading**
	Shock Load Resistance**	
	Problems of Openings, Attachments, etc.**	
Design Criteria	Base on Present Materials and Design Concepts	New Materials and Design Concepts
Fabrication Technology	Ease of Fabrication	
	Low Cost	
	Repairs and Maintenance	

* Outline based upon BuShips problem statement of August 1962.
** In author's opinion, these are the critical factors needing immediate attention.

APPENDIX I

CURRENT PROGRAMS APPLICABLE TO
DEEP SUBMERGENCE VESSEL PROBLEMS

I. PROGRAMS UNDER BUSHIPS SPONSORSHIP

A. Contract NObs-86406

"Study of the Effects of Thickness on the Properties of Laminates
for Underwater Pressure Vessels"

Aerojet-General Corporation
Azusa, California
(W. R. Rozance)

1. Object: To determine the relationship of thickness and scale
effects (thickness-to-diameter ratio) to the properties of filament
wound pressure hull structures; to investigate fabrication tech-
niques for thick filament wound pressure hulls; and to develop
design information on materials.

2. Progress: Working out glass tension programming on 6" x 11.5"
models; trying to make tubes of increasing wall thickness using
prepregs of standard materials. Expect to go to 6" thickness at
diameters of 24". Problems are how to test these constructions
adequately.

B. Contract NObs-86461

"An Investigation of the Material Parameters Influencing Creep and
Fatigue Life of Filament Wound Laminate"

Armour Research Foundation of Illinois
Chicago, Illinois
(J. W. Dally)

1. Object: To study the cyclic fatigue and creep characteristics
of filament wound models under biaxial compression loading; to
study relationship of uniaxial tests of simple specimens to biaxial
creep and fatigue tests; to investigate effect of material variables
on creep and fatigue characteristics; and to study the initiation
and propagation of microscopic cracks in filament wound laminates
under load.

2. Progress: Cyclic fatigue is being run on flat panel specimens.
It appears that the maximum stress levels possible may be higher
than expected and near 70% of the short-time ultimate strength.

Cylindrical specimens are now being set up for external hydrostatic pressure cyclic fatigue loading.

C. Contract NObs-84672

"Materials Study - High Strength High Modulus Filament Wound Deep Submergence Structure"

DeBell and Richardson
Hazardville, Connecticut
(William Eakins)

1. Object: To investigate high strength, high modulus glass fibers and resin-finish systems to develop composites having improved compressive strength and modulus.

2. Progress: Finish studies are being carried out using commercial finishes for the glass and commercial resins. NOL rings are tested for shear and flexural strength. Tubes will be tested as the ultimate type specimen for compression resistance. Only short-term strengths and boiling in water are being considered as variables in these tests.

D. Contract NObs-86347

"Drawing and Evaluation of Coarser Glass Filaments"

Narmco Industries
San Diego, California
(William Otto)

1. Object: To effect an improvement in the performance of glass filament reinforced plastics for pressure hulls through the development of optimum diameter fibers.

2. Progress: Fibers have been drawn up to 10-mil in diameter and tested in NOL ring form. The maximum compressive strengths developed have been just over 290,000 psi on the composite. They are now considering larger glass diameters and a combined fiber drawing and filament winding operation.

E. Contract NObs-86307

"Improved Resins for Deep Submergence Applications"

Aerojet-General Corporation
Azusa, California
(I. Petker)

1. Object: Evaluate currently available resin systems and determine the role of resin in filament wound pressure hulls in order to provide a basis for development of improved resins for such application.

2. Progress: Chemically different commercially available resins are being tested for compressive strength and modulus, Poisson's ratio, cyclic fatigue strength (wet and dry), long-term strength under high water pressure, resistance to buckling, shear strength and resistance to delamination, elongation and creep, handling characteristics, affinity of glass for resin, water absorption, and void content. Final evaluation will be as cylindrical specimens under external hydrostatic pressure.

F. Contract NObs-86871

"Mechanism of Water Absorption in Glass-Reinforced Plastics"

Battelle Memorial Institute
Columbus, Ohio
(Dr. W. McNeil)

1. Object: Study basic mechanism of water absorption in glass laminates; determine rate of absorption, where water goes, materials variables influencing absorption, nature and extent of deterioration, and methods of correction and improvement.

2. Progress: Small 1" diameter cast plastic and laminate cylinders are being immersed in distilled water and the moisture pick-up measured. Values are very low compared to classical data up to 10,000 psi. A diffusion apparatus will be utilized later.

G. Material Laboratory
New York Naval Shipyard Program
New York, N. Y.

1. Object: Study of mechanisms of failure; investigation of material variables (resin, glass fibers, finish, glass content, etc.); development of test methods (simple specimens vs. biaxial); large panel fatigue tests (panel size 29 1/2" x 30" x 1"); quality control and inspection (nondestructive tests); structural joint design (study of basic material parameters); and development of improved finishes based on organophosphorus compounds.

2. Progress: A survey of test methods has been published. Some work has been done on compression testing and values upward of 160,000 psi have been obtained on unidirectional laminated ring structures. Materials are being evaluated and the mechanisms of fracture are under study. A facility has been set up for external

pressure testing to very high pressure levels. New finish materials are being synthesized.

H. David Taylor Model Basin Program
    Carderock, Maryland

    1. Object: Review and evaluate orthotropic shell theory; test filament wound models (short-term, cyclic fatigue, creep and dynamic loading) to determine feasibility and obtain design information; investigate composite metal-plastic constructions and design details; and relate elastic constants to design of filament wound materials.

    2. Progress: New structural concepts in respect to both materials and designs are being developed and tested. Glass reinforced models, as produced by industry, are being evaluated.

I. Naval Research Laboratory Program
    Washington, D. C.

    1. Object: Basic studies to determine mechanisms of failure and to relate polymer structure to performance under deep submergence exposure.

    2. Progress: Modified polymers are being tested by classical methods to relate structure to performance.

II. PROGRAMS UNDER BUWEPS SPONSORSHIP

    A. Contract N-60921-7018

        "Compression Testing of Filament Wound Reinforced Plastic Laminates"

        A. O. Smith Corporation
        Milwaukee, Wisconsin
        (T. G. Roskos)

        1. Object: Determine a method of measuring the compression properties of NOL filament wound rings; design and fabricate a compression tester and demonstrate its feasibility; and develop a body of test data on rings to evaluate (a) winding variables, (b) roving construction, and (c) long-term water immersion at 50°F and 150°F.

        2. Progress: A compression tester has been developed and proven in. See "Current NOL Ring Studies and Test Methods," ASTM-Navy Symposium on Standards for Filament Wound Reinforced Plastics, 6-7 June 1962. Data are being collected on the effects of five process and environmental variables.

B. Contract NOw-61-0613-d

"Improvement of Reinforced Plastics"

General Electric Company
Space Sciences Laboratory
Philadelphia, Pennsylvania

1. Object: Study hollow glass filaments for use as reinforcements in plastics deep submergence vessels.

2. Progress: Hollow glass fibers are being drawn and tested for the more efficient reinforcement of compression members. The advantages of using hollow fibers in compression are analyzed mathematically.

III. PROGRAMS UNDER AIR FORCE SPONSORSHIP

A. Contract AF 04(64-7)-617)

"Improved Structural Composites"

General Electric Company
Philadelphia, Pennsylvania

1. Object: To improve the mechanical efficiency of glass reinforced structures.

2. Progress: Hollow filaments of type 172 E glass have been drawn and tested. Tensile strengths from 30,000 to 112,000 psi have been obtained. Specific compressive strengths up to 274,000 psi have been obtained as compared to a value of 161,200 psi for solid filaments.

APPENDIX II

INTERLAMINAR SHEAR CONTROL FOR
REINFORCED PLASTICS EXTERNAL PRESSURE VESSELS

INTRODUCTION

1. One of the demands of underwater structures is that they resist
static collapsing loads for very long periods of time. This is a demand
that is quite different from any short-term loading requirement. The
problems involved, as evidenced by very poor long-term performance of
plastics vessels whose dynamic pressure resistance was outstanding, are
not as yet fully understood. Work is needed to gain this understanding
and to find ways of improving the long-term hydrostatic pressure resistance
characteristics of reinforced plastics structures.

BACKGROUND

2. Reinforced plastics structures vary in their resistance to collapse
under external hydrostatic pressure. They also perform quite differently
in time-to-failure tests under conditions of constant long-term hydrostatic
loads (ref. (II-a)). Two classes of glass reinforced plastics structures
have been studied: glass fabric and glass roving reinforced. It was deter-
mined that the glass roving vessels were the stronger on dynamic loading.
They resisted pressures as high as 1,760 psi, while the average strength
for a typical fabric reinforced vessel of the same design was 1,000 to
1,100 psi. However, on time-to-failure tests at pressure levels equal to
60% of ultimate strength, the roving reinforced vessels failed in 6 to 17
days, while the fabric reinforced vessels withstood these conditions for
from 10 to 11 1/2 months. Moisture effects are not considered of con-
trolling importance in the above data, as one might expect, since the
resin used with the roving has been shown to be considerably more resistant
to moisture than that used in the glass fabric vessels.

3. One reason postulated for the above performance is that failure
in these long-term tests is initiated through creep and shear in the resin
matrix. In the case of the fabric reinforced vessels, the plys of rein-
forcement are mechanically bound together in the one plane and resin creep
is limited primarily to the layers in between the plies. However, with a
roving reinforced construction, there is no real mechanical tie between
rovings, and so resin creep can take place in all directions with a mini-
mum of restrictions. Such creep permits the vessel to deform and lose its
roundness and then to go into an instability failure mode as the shear
forces build up. The problem then becomes one of reducing the initial
creep and the final shear effects. Ideally, a situation would be created
whereby the entire construction acts as if it were of an isotropic material.
One approach to this is to tie the plies of fabric or roving reinforcements

together through the resin layers so that they are mechanically caused to act in concert in all three dimensions.

4. Several practical approaches are immediately clear toward providing the above conditions and should be evaluated. Meanwhile, still other ideas should be sought and tested.

OBJECT

5. To investigate practical means for controlling creep and shear characteristics of the resin matrix in a laminate structure without suppressing its other desirable properties.

PROGRAM

6. The program will be in three phases. Phase (A) will consist of a series of empirical approaches toward resin creep and shear control. In phase (B), model constructions will be made or purchased from various firms to compare the properties of different unique constructions. Phase (C) will be an analysis phase for (A) and (B).

Phase (A)

7. NOL rings and small tubes (approximately 6"0 I.D. x 12" length) will be fabricated with both glass fabric and glass roving reinforcements. A typical epoxy resin formulated for high heat distortion properties combined with good handling characteristics will be used as the matrix material. This will be compared with a very flexible formulation. The following process variations will be investigated.

a. Interleaving of fabric and roving.

b. Introduction of chopped glass roving or milled glass fibers during winding.

c. Introduction of glass flake during winding.

d. Development of roving winding pattern interleaving techniques.

e. Shingle winding with a tape material.

f. Use of roving made of staple glass fibers or whisker materials.

g. Impregnation of the glass with a flexible resin followed by lamination with a rigid resin.

h. Effect of laminate quality (flaws) on properties.

i. Other approaches toward a "three-dimensional" laminate structure.

Rings will be evaluated first, then the most promising ideas will advance to the tube study.

    8. The tests that will be considered are:

        a. On NOL rings:

            (1) Tensile Strength

            (2) Compression Strength

            (3) Interlaminar Shear Strength

            (4) Flexural Strength

            (5) Flexural Creep

            (6) Impact Strength

        b. On small tubes:

            (1) Circumferential Ring Shear Strength

            (2) Resistance to Diametrical Loading

            (3) Collapsing Pressure

Phase (B)

    9. Half-scale mine models will be fabricated as guided by the data from Phase (A). Models will be purchased from industry to establish the quality of their fabrications and to test out any unique ideas they may have on shear control.

    10. These models will be tested for:

        a. Collapsing Pressure

        b. Time-to-Failure Characteristics

        c. Circumferential Ring Shear

Phase (C)

    11. The data from phases (A) and (B) will be analyzed to show how improved resistance to external pressures may be gained through materials and process variations. An effort will be made to show the contribution of the components in a composite to its mechanical properties and the contribution of these properties to structure performance in an underwater service environment.

12. It is expected that all three phases will operate concurrently with the ring and small tube work guiding the model work.

REFERENCES

(II-a) NavOrd Report 6165, "Reinforced Plastics as Materials of Construction for External Pressure Vessels (U)," by F. Robert Barnet, Marlin A. Kinna and Walter T. Johnson, 14 February 1961.

APPENDIX III

SHOCK LOADING OF REINFORCED PLASTICS
EXTERNAL PRESSURE VESSELS
(Shock Studies)

INTRODUCTION

1. An underwater military structure must reliably be able to resist
static pressure loadings in order to perform its workaday mission. In
addition, in times of attack by the enemy, it must be able to withstand
shock pressure overloadings of varying durations and of high magnitudes.
Not only must these mechanical forces be withstood, but it must be accom-
plished without causing other minor damage to the structure which might
lead to water leakage, loss of fastenings, etc. With metal structures,
certain knowledge exists for predicting such performance. However, with
the consideration of reinforced plastics as materials of construction for
deep submergence vessels, many questions quickly arise as to their suit-
ability for this type of service.

BACKGROUND

2. The ability of a glass reinforced plastics structure to withstand
shock loadings while under moderately low static hydrostatic pressures
has not yet been explored in any great detail, and nothing has been done
at high static loadings. As reported in NavOrd Report 6165 (ref. (II-a)),
simple small tubes of different materials combinations have been sub-
jected to hydraulic shock loadings and a very limited amount of data has
been collected. This work was all with fabric reinforced polyester and
epoxy resin formulations and was limited to only two variations in geometry.

3. Larger, more complicated glass fabric reinforced plastics
structures, in the form of half-scale mines, were evaluated for counter-
mining, reference (III-a). Here again, the tests were limited - a total
of 14 vessels - and gave only "go-no-go" information.

4. Some evaluations were next made on full-scale Mk 57 mine cases.
These again were of a countermining nature and give little information
other than that typical countermining pressures could be empirically
designed for and withstood. From these tests, it became apparent that
quality of the construction is of great importance. Laminates with resin
rich areas, starved spots, and delaminations could not be shock loaded
without severe or catastrophic damage. On the other hand, the same
materials in the same design, when the quality of construction was good,
passed all tests. In these tests it was also evident that the weak points
of the designs were those places where entrances to the interior of the
case had to be provided and where metal inserts were incorporated. Ad-
hesive joints at these points, in fact, became the limiting element in the

ability of the case to withstand shock loading, reference (III-b). It was further noted that inside structural members and attachments thereto gave difficulties also.

5. From these data, it is known that plastics structures can be made which will meet moored mine service requirements. However, an understanding of how such a structure absorbs shock loadings or of the strength limits of glass reinforced plastics materials and designs under shock conditions has not yet been set forth.

6. In considering a program in the shock area, the most direct approach appears to be through the use of model structures. With metals, some progress in design has been made using classical strength properties, but even here model tests soon become necessary to give assurance that the design is satisfactory (ref. (III-c)). This being the general approach with metals, which are ideal isotropic materials compared with the reinforced plastics, the design problem is obviously even greater with the nonmetallics. It is not known now, in the present state-of-the-art, what can be accomplished by measuring the more standardized dynamic properties of these materials and trying to translate the data into terms of structural shock resistance. Later it may be possible to collect data on the equation of state for interesting materials and to apply this information to the practical situation.

OBJECT

7. The object of this program is to expand the knowledge of the hydraulic shock loading resistance characteristics of glass reinforced plastics materials and structures.

PROGRAM

8. The shock loading program will be in four parts:

    A - UWX shock testing of small models.

    B - Explosive shock testing of small and large models.

    C - A study of stress risers in structures and their effect on shock resistance.

    D - A fundamental study of the resistance of plastics materials to shock.

Phase A

9. The NOL UWX tester (ref. (III-d)) will be used as the means of loading small model structural specimens. These will be right circular cylinders, approximately 3 inches in diameter by 7.5 inches in length,

closed on the ends by metal plates. Length and diameter dimensions will hold, but as the tests progress, changes in wall thickness and circumferential reinforcing ribs will be introduced. The materials to be selected will be rigid and flexible epoxy resins reinforced with glass fabric and glass rovings. As methods develop on other studies to improve interlaminar shear resistance, these variations will also be incorporated.

10. Conditions in the UWX device will range up to 1000 psi static load. Simultaneously with static loading, impulse loadings as high as 2500 psi will be employed. Later, with some modification of the equipment, peak impulses of 4000 psi may possibly be obtained. Static collapsing pressure tests, as well as other standard identity tests, will also be made to characterize each type of specimen.

11. It is expected that a limited amount of instrumentation will be required so as to measure specimen responses and deformation under load. The possibility of utilizing photostress techniques will be explored.

12. Under the above conditions, primarily materials, but also limited geometrical factors, will be evaluated to indicate resistance to deep submergence shocks and to aid in the selection of materials and designs for the production of the Phase B specimens.

Phase B

13. In this phase, model structures ranging from the specimens of Phase A to half-scale mine case models and idealized plate specimens will be evaluated under shock loading as produced by explosive charges in water (ref. (III-e)). This work will be carried out to further evaluate materials and designs. Under these conditions it will be possible to produce higher peak pressures than in the UWX tester, although it will not be possible to have the high static loads. The static loads will be determined by river, bay, and tank depths, or at any other spot where firings may be made. With explosive shocks it will also be possible to vary the impulse from that of the ordinary rapidly decaying shock pulse to a condition of relatively slow decay. In this latter case, the impulse wave, in effect, engulfs the specimen and tends to apply more of a hydrostatic pressure on it.

14. The specimens under test will be characterized by short-term collapse and identity tests. Under shock loadings, the principal variables will be peak pressure and duration of shock wave. The specimens will be strain gaged to measure axial and circumferential deformations and membrane stress and deformations. Accelerometers will be considered for measurement of model movement and the movement of one part of the model relative to other parts.

15. Under the existing test conditions, charges as great as 80 pounds of TNT in depths up to 40 feet will be utilized. Whenever possible, models will be worked into other test programs so as to obtain a greater variation in test conditions.

III-3

16. From these tests, the most satisfactory glass reinforced plastics materials for resistance to underwater shock should become evident.

Phase C

17. Phases A and B are limited to the study of ideal specimens, i.e., ones without openings, attachments, or other stress risers. However, from the past practical experience, these factors appear to be the controlling ones in determining the shock resistance of a piece of ordnance.

18. Phase D will be a study of various stress risers in the ideal half-scale mine model specimen. Only models made with the most shock resistant materials from Phase B will be considered here. Various openings and closures will be designed and shock tested, as determined most appropriate in the Phase B Studies. Internal methods of attachment will also be investigated and analyzed. It is expected that the instrumentation will be the same as for Phase B.

19. From these tests new concepts of openings, closures, and attachments will be developed and data will be collected on their performance characteristics under shock loading.

Phase D

20. Phases A, B and C are of an empirical nature directed toward the development of engineering type data and represent the most direct approach to general shock resistance study. Simultaneously with these phases, however, it is well to explore the resistance of these highly anisotropic reinforced plastics to shock on a more fundamental basis. Some exploratory work on plastics has been done impacting conical specimens with a shock wave from a detonator (refs. (III-f) and (III-g)). The Laboratory has also done other work on aluminum, copper, boron nitride, pyrolytic graphite, nylon, and methymethacrylate, as discussed in part of reference (III-g). From these latter tests it has been possible to explore to a limited extent the equation of state for materials under shock conditions using special techniques developed at NOL.

21. It is planned to utilize NOL's special shock study capabilities (ref. (III-h)) and to submit some of the materials to this test which are of most interest in Phases A and B above. Specimens will be made of rigid and flexible epoxy resins, in the form of resin castings with and without glass fabric and glass roving reinforcement. The laminates will be tested with the shock pulse both parallel and perpendicular to the direction of the glass. In addition, polyethylene of a high shock resistant variety will be included.

22. In these tests, attempts will be made to measure or gage the acceptance of the shock wave by the materials, shock wave velocity in

the material, free side spalling tendencies, and transfer of the shock through the free side to an acceptor back-up layer.

23. From these data and other general observations and measurements which may be devised, an attempt will be made to gain a greater understanding of how these materials perform under shock and of how this information might be translated and utilized in the practical situation.

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APPENDIX IV

CREEP AND FATIGUE STUDIES OF FILAMENT
WOUND MATERIALS FOR UNDERWATER USE

INTRODUCTION

1. The need for more knowledge of reinforced plastics in the external pressure vessel field is growing continuously. Filament wound materials show great promise for use in deep submergence vehicles, as has been demonstrated by DTMB and others. The glass-filament wound materials, or a combination of materials utilizing this material as a major constituent, appear to have an almost unique potential for deep submergence structures.

BACKGROUND

2. Although laboratory work at NOL, the A. O. Smith Corporation, the New York Naval Shipyard's Materials Laboratory, Narmco, etc. is leading to information on compression properties, such as short-time strength and modulus, there is very little known or being done to determine the time-dependent characteristics of these materials. The work at Armour Research Foundation for the Bureau of Ships to date has involved some creep and fatigue work in compression but only on flat parallel glass laminates; work on structures will come in the future.

3. The NOL ring compression testers at NOL and at A. O. Smith are beginning to give valuable data on compressive properties on a short-time basis. Individual compression strength values are already running nearly as high as 300,000 psi on a composite basis. The important determination now is the percentage of this original strength that will be available on a long-term basis.

4. A ring in the compression tester fails in a catastrophic manner and one might surmise that he has witnessed a true compression failure. Upon examination of the specimen, however, in many instances, there seems to have been delamination followed by a bending inward of the inner fibers of the ring, and a fracture that is jagged and which represents considerable energy having been released in a large volume of the specimen.

5. If the failure of the ring begins by delamination, followed by bending, it would seem then that the behavior of these materials under long-term and cyclic compression loads could be better understood through interlaminar shear-creep and compression creep and fatigue studies in addition to standard ring compressive tests. The NOL ring, or sections of the ring, can be very easily tested for interlaminar shear, and a test can be readily set up to get creep information at a percentage of the shear strength of any system.

OBJECT

6. To study the creep and fatigue characteristics of glass filament unidirectionally reinforced plastics.

PROGRAM

7. It is proposed that a method of high speed photography be used to analyze the failure mode of rings in compression. From such pictures it should be possible to see local bending or shear failures which might occur prior to total failure of the ring. With shear data available, a correlation between compression properties and shear will be attempted (and with material and process variations).

8. From the above, a group of rings with wide differences in properties will be selected. First, sections of these rings will be tested in a flexural-type creep apparatus for time-to-failure at selected load levels. Second, rings will be evaluated in the compression tester for fatigue. A ring will be loaded to given percentage of its ultimate strength, held for a period, the load released and then the cycle repeated a determined number of times.

9. Since such a program can get fairly involved, techniques of the statistical design and analysis of experiments will be used to limit the number of samples and test conditions needed and still permit trends and significant variations to be recognized. Specimen variables will be kept to a minimum and will probably involve one glass formulation, one glass finish, three to five resin systems, three to five process variations, and three to five test stress levels.

10. From these efforts a better understanding of compression failure and its relation to materials variation would be sought. It is expected that the creep and fatigue data would enable better selections to be made of materials for practical application as well as better relate these general properties to materials variations.

(Based on a program by S. P. Prosen)

APPENDIX V

ENVIRONMENTAL STABILITY OF MATERIALS
FOR UNDERWATER VESSELS
(Materials Deterioration)

INTRODUCTION

1. When considering reinforced plastics materials for the con-
struction of deep submergence vessels, one of the critical questions
presented relates to the rate at which these materials may lose their
properties when immersed for extended times in sea water. If this rate
is too great, then composite plastics would be of only very limited
interest.

BACKGROUND

2. Permanence of glass reinforced plastics in severe environments
is not exactly a new question. It has been asked and investigated to
various extents in the past in connection with many ordnance developments.

3. Outdoor weathering is probably the most investigated environ-
mental effect. The Forest Products Laboratory, Madison, Wisconsin and
the Naval Materials Laboratory, New York, New York have both done much
work in this area. It has been shown that phenolic and epoxy resin
systems generally hold up better than the polyesters, even though there
is some loss of strength in all cases (ref. (V-a)).

4. In reference (V-b), phenolic, polyester and epoxy glass cloth
laminates were evaluated for flexural strength characteristics after
Mil-Std-354 temperature-humidity cycling (JAN cycle). The materials were
also temperature cycled according to the JAN schedule but with the
humidity uncontrolled. From these experiments, it was evident that
laminates could be made whose properties showed no serious changes in
the two environments. The key to this appeared to be the selection of
a resin-catalyst or curing agent-glass finish combination which had high
heat distortion properties.

5. Stanford Research Institute did work on laminates for antennae,
and their data (ref. (V-c)) correlate in part with those of reference
(V-b). SRI found that in a 160°F, 95% RH environment both polyesters
and epoxies suffered loss of flexural strength. The epoxies were superior
and the general purpose resins were the poorest performers. They con-
cluded that tropical conditions were the most severe conditions to be
encountered.

6. Later, in reference (V-d), the type of studies of reference (V-b)
were expanded and some data were presented on compressive strength

variations. However, in these tests continuous exposure to 160°F, 95% RH was used in place of the heat cycle of the original work. A heat resistant polyester and a number of the more heat resistant epoxy materials performed very well.

7. Reference (V-d) also reported tests made on tubes of different materials after various water immersion periods (at insignificant pressures) up to 12 months. These limited data apparently confirm those data gathered on flexural and compressive strength. However, in tube form, the materials did not show the significant variations they did in standard specimen form when tested in the more severe environments.

8. Another point which should be recognized and which is implicit in the data reported in reference (V-d) is that a "bad" resin will do a "good" job in a model test. A polyester resin mixture - P43/P13/Styrene - which performed poorly in the environmental resistance tests (refs. (V-b) and (V-c)), when fabricated into a half-scale mine model, gave a rather remarkable performance. Its performance raises some question as to how severe moisture deterioration really is when the vessel is wetted on the outside and maintained dry on the inside. It may be postulated that under these conditions there is a moisture gradient in the laminate with the highest content being on the wet side. The gradient probably decreases at an exponential rate and, therefore, most of the laminate thickness is really at quite a low moisture content. As a result, the properties of the bulk of the laminates may not be decreased by any significant amount under practical service conditions.

9. Again, in reference (V-e), the results of outdoor weathering and 14 and 28-day JAN cycling on glass filament reinforced plastics structures are discussed. Here, through burst tests of roving reinforced tubes, it was demonstrated that the more temperature resistant epoxy resin formulations show the best permanence characteristics.

10. It would appear from the work that has been done that glass laminate materials age well when there is no excessive moisture present. However, when the humidity is high or when water immersion is part of the exposure and when the temperature is high, deterioration of mechanical properties takes place. This deterioration may be countered to a degree by the proper choice of resins, curing agents and catalysts, and glass finishes; the more heat resistant combinations being preferred. However, with practically all the data being collected by testing standard specimens from flat plates, and with very little data available from work on structures under service conditions, it is not too clear what the true situation is with a piece of ordnance. Translation of our present knowledge to the more practical situation, therefore, needs study.

OBJECT

11. It is the aim of this program to more specifically elucidate the deteriorative effects that continued immersion in sea water may have on
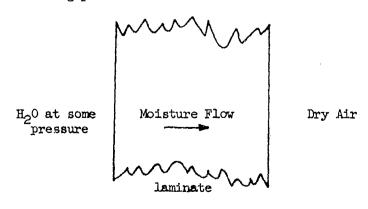
glass reinforced plastics structures.

PROGRAM

12. The approach to showing the degree of property deterioration in plastics structures will be in three phases:

A. The effect of moisture on the mechanical properties of classical specimens will be studied.

B. The transmission of moisture through a laminate and the resultant moisture absorption profile will be studied.

C. The data from A and B will be analyzed to establish the degree of property deterioration in structures which may be anticipated and to isolate the factors controlling the overall phenomena. An attempt will be made to place these concepts in a mathematical form useful for prediction purposes.

Phase A

13. Both glass cloth and glass filament reinforced materials will be considered. Resin formulations will be selected from the classes of polyesters, epoxies and phenolics. In addition, consideration will be given to general purpose (nominal heat resistant), moderately heat resistant, and highly heat resistant resins - catalyst or curing agent - glass finish systems. Standard specimens of panel or ring types will be prepared, conditioned to varying moisture contents for different time periods, and tested for mechanical strength retention. Various environmental exposures, such as JAN cycle, may also be considered for these studies. With these data, plots of strength properties versus moisture content will be constructed.

Phase B

14. The following practical situation will be assumed to exist:

H_2O at some pressure   Moisture Flow   Dry Air

laminate

Water will pass through the laminate at some overall rate dependent upon the latter's effusion and diffusion characteristics. At first the rate will be variable but will then develop a steady state.

15. To establish the steady-state moisture absorption profile through the laminate thickness, water permeability tests will be made on panels at different water pressures. A type of open screen electrode will be considered for placement between each laminate layer or alternately, individual one-ply laminates will be stacked with screen electrodes in between to make up the test specimen. During the measurement of the composite moisture transmission characteristics (MVTR), either electrical resistance or capacitance will be measured. This will give a clue as to the typical shape of the moisture gradient within the composite all during the test and until steady state is obtained. Other tests will be made to determine the moisture pickup of small resin or laminate samples and their corresponding electrical properties. With these latter data, the electrical readings on the MVTR panel will be converted to a moisture content gradient plot. By comparing the data of Phase A with this plot, it will then be possible to determine at what distance into the panel the deteriorative effects of water are significant, or the percentage of unaffected material remaining can be estimated. Thus, it should be possible to predict the resistance to moisture deterioration to be expected of a typical structure. It is expected that this will vary with resin formulation, glass finish and glass, as well as with geometrical factors and the test conditions selected.

16. Other experiments will be run, as above, but on tubes so that the water pressure may be varied widely and the effects of mechanical loading brought into the study. Consideration will be given to different coating materials to be applied to the wet side and thereby reduce moisture permeation into the laminate.

17. Temperature will also be a variable to consider.

Phase C

18. The data from A and B will be analyzed and an attempt will be made to establish a mathematical basis for predicting the life of a structure in water. The first trial will assume moisture permeability as diffusion controlled and calculations will be made on this basis for comparison with the experimental data. This concept will then be modified as indicated. An attempt will be made to describe the mechanism or mechanisms which control the passage of moisture into and through laminate materials under idealized underwater service conditions. It is also expected that it will be possible to set forth guidelines for the selection of materials for underwater usage.

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			BIBLIOGRAPHIC (SUPPL., VOL., ETC.)		

SUBJECT ANALYSIS OF REPORT

DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Reinforced	REIN	High pressure	HIGP	Attachments	ATTC
Plastics	PLAS	Pressure	PRES	Pressure vessels	PRER
Underwater	UNDE	Weight	WEIG	State-of the-art	HOWE
Ordnance	ORDN	Problems	PRBL		
Deep	DEPT	Creep	CREE		
Submergence	SUBG	Fatigue	FATI		
Constructions	CONS	Shock	SHOC		
Submarine	SUBM	Loading	LOAD		
Hulls	HULL	Resistance	REST		
Glass	GLAS	Structural	STRC		
Lightweight	LGHT	Joints	JOIN		
Materials	MATE	Openings	OPEN		

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    (NOL technical report 62-206)
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